APPLICATION OF COMPUTATIONAL MODEL ON BERM BREAKWATER DESIGN

by

J.W. van der Meer

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The development of a computational model on dynamic stability is summarized. The model is able to predict profiles of slopes with an arbitrary shape under varying wave conditions. The model is used to design a berm breakwater in relatively deep water (18 m) and for severe wave conditions (H_s = 7.6 m). First the dimensions of the berm breakwater were optimized with respect to the amount of required armour stone. Then the influences of water depth, stone class and wave climate were investigated. Finally the stability after the first storms was analyzed in more detail.

Résumé

L'étude résume la mise au point d'un modèle de calcul de la stabilité dynamique. Ce modèle permet de prédire des profils de pentes avec une forme arbitraire dans des conditions de vagues variables. Le modèle est utilisé pour concevoir un brise-lames à risberme en eau relativement profonde (18 m) pour des conditions de vagues rigoureuses (H_s = 7,6m). Les dimensions du brise-lames à risberme ont d'abord été optimisées en fonction de la quantité de pierres de carapace nécessaires. Les influences de la profondeur d'eau, de la classe de pierres et du régime des vagues ont ensuite été étudiées. Enfin, la stabilité après les premières tempêtes a été analysée de façon plus détaillée.

Application of computational model on berm breakwater design

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Abstract

The development of a computational model on dynamic stability is summarized. The model is able to predict profiles of slopes with an arbitrary shape under varying wave conditions. The model is used to design a berm breakwater in relatively deep water (18 m) and for severe wave conditions (H_s = 7.6 m). First the dimensions of the berm breakwater were optimized with respect to the amount of required armour stone. Then the influences of water depth, stone class and wave climate were investigated. Finally the stability after the first storms was analyzed in more detail.

Dynamic stability

Most breakwaters and revetments are designed in such a way that only little damage is allowed for in the design criteria, damage being defined as the displacement of armour units. These criteria demand large and heavy rock or artificial concrete elements for armouring. A more economic solution can be a structure with smaller elements, profile development being allowed in order to reach a stable profile.

The $H_s/\Delta D_{n50}$ parameter can be used to give the relationship between different structures, see Figure 1, where: H_s = significant wave height, Δ = relative mass density and D_{n50} = nominal diameter of average stone mass.

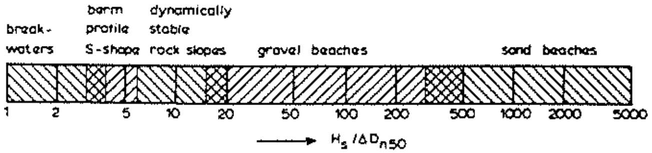

Figure 1 Type of structure as function of $H_s/\Delta D_{n50}$

Small values of $H_s/\Delta D_{n50}$ give structures with large armour units. Large values imply gravel beaches and sand beaches. Figure 1 gives the following rough classification:

- statically stable breakwaters: $H_s/\Delta D_{n50}$ = 1 - 4
- berm breakwaters and S-shaped profiles: $H_s/\Delta D_{n50}$ = 3 - 6
- dynamically stable rock slopes: $H_s/\Delta D_{n50}$ = 6 - 20
- gravel beaches: $H_s/\Delta D_{n50}$ = 15 - 500
- sand beaches: $H_s/\Delta D_{n50}$ > 300

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Van der Meer and Pilarczyk (1986) described a computational model for the profile development of rock slopes and gravel beaches. The area given by $H_s/\Delta D_{n50}$ = 3-500 was covered by this computational model. The model will be described briefly and will then be applied to the design of berm breakwaters. This means that the application is focussed on the area given by $H_s/\Delta D_{n50}$ = 3-6.

Governing variables

The governing strength variables are:
stone size, grading of the stone, shape of the stone, initial slope and shape of the foreshore.

In the paper the size of armour units or gravel is referred to as the average mass of graded rubble or gravel, W_{50}, or the nominal diameter, D_{n50}, where:

$$D_{n50} = (W_{50}/\rho_a)^{1/3} \qquad (1)$$

where: D_{n50} = nominal diameter (m)
W_{50} = 50% value of the mass distribution curve (kg)
ρ_a = mass density of stone (kg/m³)

The relative mass density of the stone in water can be expressed by:

$$\Delta = \rho_a/\rho - 1 \qquad (2)$$

where: Δ = relative mass density (-)
ρ = mass density of water (kg/m³)

The grading of the stone is expressed here by D_{85}/D_{15}, where the subscripts refer to the 85 and 15 percent value of the sieve curve, respectively. The shape of the stone can be angular, rounded or flat. The initial profile can vary from a uniform slope to a berm profile or a structure with a low crest.

The governing load variables are:
significant wave height H_s, average wave period T_z, storm duration given by the number of waves, N, the angle of wave attack, ϕ, and water level (tide).

Conclusions on test results

One of the main conclusions of the model investigation (Van der Meer and Pilarczyk (1986)) was that in spite of different initial slopes, the same profile is reached for a large part of the total profile. This part ranges from the crest to the transition to a steep slope (the step) at the deep water end of the profile. Figure 2 gives the same profiles for a 1:5, a 1:3 and a 1:1.5 uniform initial slope. Only the upper and lower parts of the profile are in fact dependent on the initial slope. The direction of transport of material and the position of the profiles is, of course, largely influenced by the initial slope.

The same conclusion was drawn from the results of the tests in which the influence of tide was investigated. In fact, the profile changed directly with changing water level, providing that $H_s/\Delta D_{n50}$ > 10 -15.

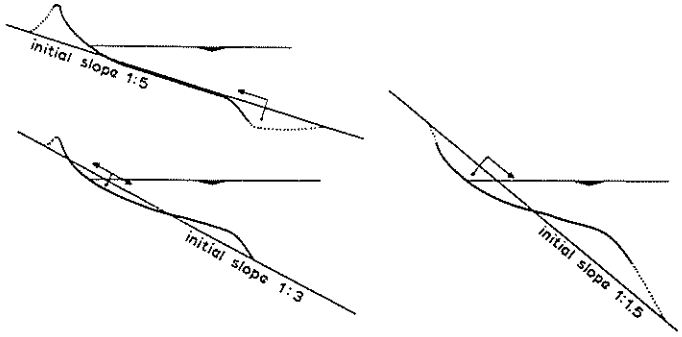

Figure 2 Profile obtained with different initial slopes

Static stability is largely dependent on the initial slope, as is clearly expressed by the well known Hudson formula. Of course, for dynamically stable structures which are almost statically stable, the initial slope has also influence on the profile. It can be stated that, for $H_s/\Delta D_{n50}$ < 10 - 15 the initial slope has influence on the profile.

From the analysis it could be concluded that the wave spectrum shape had no or only minor influence on the profile, provided that the average wave period was used to compare the tests, and not the peak period. The same conclusion was found for static stability by Van der Meer and Pilarczyk (1987). The grading of the material also has no or only minor influence on the profile, using the nominal diameter, D_{n50}, as a reference.

Summarizing, from comparison of profiles it was concluded that wave height H_s, wave period T_z, number of waves, N, and nominal diameter D_{n50}, all have influence on the dynamic profile.

The spectrum shape and the grading of the material have no or only minor influence; the initial slope has no influence on a large part of the profile for $H_s/\Delta D_{n50}$ > 10 - 15.

Development of a model on dynamic stability.

On the basis of the conclusions described above a model was developed to describe the dynamic profile. Two points on the profile are very important. These are shown in Figures 3 and 4, where profiles for a 1:3

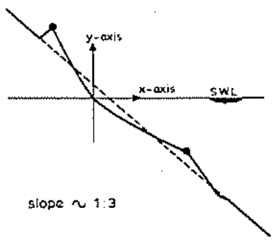

Figure 3 Schematized 1:3 profile

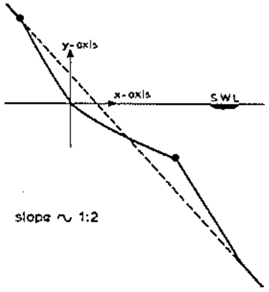

Figure 4 Schematized 1:2 profile

and 1:2 uniform slope are illustrated schematically. The first point is the upper point of the beach crest and the second point the transition below SWL from the gentle part to a steeper part. The local origin is chosen at the intersection of the profile with the still water level.

Figure 5 shows the model for a dynamic profile. A 1:5 uniform initial slope is shown with a high beach crest and a step. The profile is schematized by using a number of parameters all of which are related to the local origin or to the water level. The beach crest is described by the height, h_c, and the length, l_c. The transition to the step is described by the height, h_s, and the length, l_s. Curves, described by power functions, start at the local origin and go through these two points. The run-up length is described by the length, l_r. The step is described by two angles, β and γ. Finally, the transition from β to γ is described by the transition height, h_t.

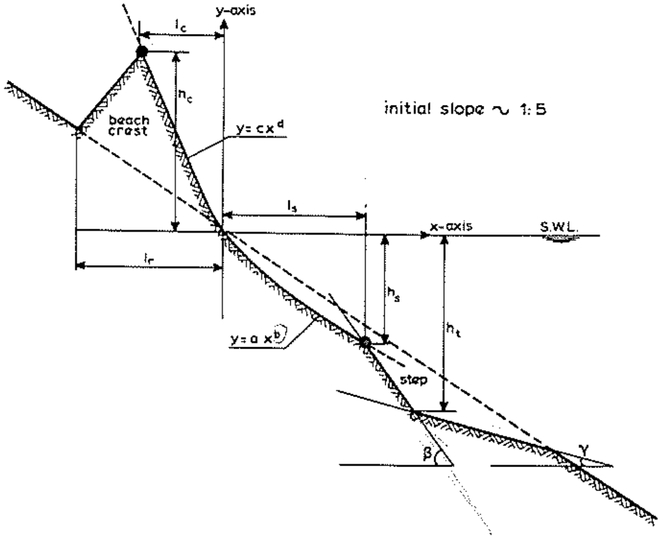

Figure 5 Model for dynamic profile

The final analysis resulted in relationships which described the above profile parameters as a function of the boundary conditions.

These relationships for the height and length parameters, the power curves and the two angles β and γ were used to develop a computer program. For low $H_s/\Delta D_{n50}$ values (smaller than 10-15) an equivalent slope angle was introduced and used in the relationships. This program can be used to calculate the profile, starting from an arbitrary slope and with varying water levels (tide) and wave conditions.

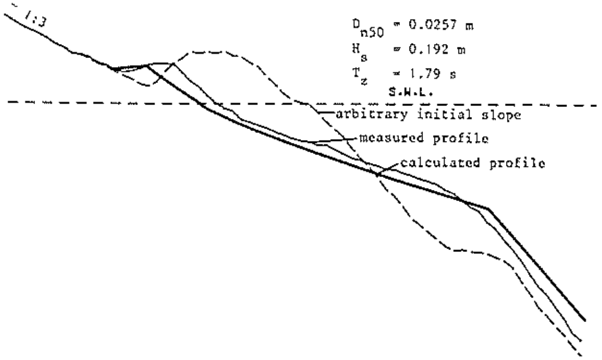

Figure 6 Measured and calculated profile developed from an arbitrary initial slope

In one test the man who constructed all the models was asked to build an arbitrary slope in the way he preferred. Figure 6 shows the slope he constructed and the measured and computed profile. The initial slope had an upper slope of 1 in 3 and a lower slope, with some irregularities, varying between 1 in 1.5 and 1 in 2. First the profile is calculated with the local origin at the intersection of the initial profile with the still water level. It is clear that this is not the right position of the profile. By means of an iteration process the profile is moved along the still water level untill the mass balance is fulfilled.

Berm breakwater concept

The berm breakwater can be regarded as an unconventional design. Displacement of armour stones in the first stage of its life time is accepted. After this displacement (profile formation) the structure will be more or less statically stable. The cross-section of a berm breakwater consists of a lower slope 1:m, a horizontal berm with a length b just above high water, and an upper slope 1:n. The lower slope is often steep and close to the natural angle of repose of the armour. This means that m is roughly between 1 and 2.

During the design of a berm breakwater the following aspects should be considered:

- Optimum dimensions of the structure: m, n, b and crest height, obtained for chosen design conditions.
- Influence of water depth.
- Influence of stone class.
- Influence of wave climate.
- Stability after first storms.

The following boundary conditions are chosen for the design of a berm breakwater which were in fact taken from a project in the Spanish Mediterenian:

- waterdepth up to 18 m.
- no tidal range
- wave climate: 1/1 year : H_s = 4.7 m T_z = 8.2 s
  1/5 years : H_s = 5.9 m T_z = 9.0 s
  1/50 years: H_s = 7.6 m T_z = 10.0 s

- storm duration of 6 hours
- available stone classes: 0.5 - 9t, D_{n50} = 1.01 m
  1 - 9t, D_{n50} = 1.11 m
  3 - 9t, D_{n50} = 1.19 m
- relative mass density: Δ = 1.55
- berm 0.5 m above the still water level (SWL).

Design of berm profile

The optimum values of m, n, b and crest height will be established for a water depth of 18 m and the 1/50 years wave conditions, H_s = 7.6 m and T_z = 10.0 s. This means that the structure is designed for $H_s/\Delta D_{n50}$ = 4.9. The optimum value of b can be established for various combinations of m and n and for the stone class with D_{n50} = 1.01 m. The criterion for the optimum value of b was the minimum value for which the upper point of the beach crest (see Figs. 3 and 4) was not a part of the erosion profile. In fact the upper point of the beach crest should lay on the initial slope,in order to prohibit erosion of the crest of the initial profile

For each combination of m and n the minimum value of b was obtained iteratively, using the computational model. Figure 7 shows the minimum lengths of the berm as a function of the upper and lower slope angles. The berm length decreases almost linear with increasing lower slope, m. The same conclusion can be drawn for the upper slope, n.

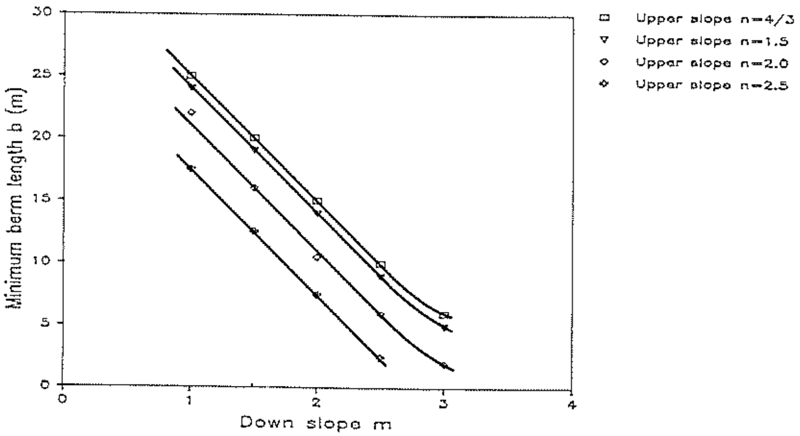

Figure 7 Minimum berm length as a function of down slope and upper slope

Figure 7 gives no information on optimum values for m and n. In fact Figure 7 gives various structures with more or less the same stability (no erosion on the upper slope). Therefore an other criterion is introduced. The amount of stones required for construction can be minimized, giving the cheapest structure. The height of the upper point of the beach crest amounted from 7 to 9 m. The crest height of the initial profile was chosen at a fixed level of 9.5 m above SWL which is about 1.25 times the significant wave height. The area of the cross-section from the crest to the toe of the structure gives a measure of the amount of

stones required. This amount, B, was plotted versus the lower slope and for various upper slopes in Figure 8. The berm lengths are the same as in Figure 7.

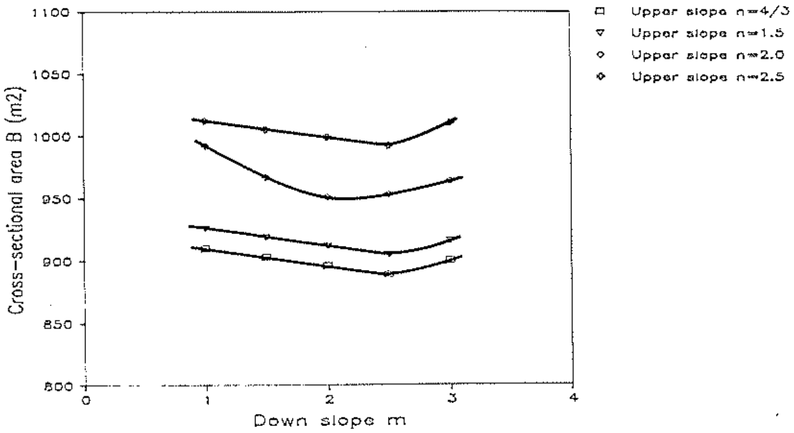

Figure 8 Cross-sectional area as a function of down slope and upper slope

From Figure 8 it can be concluded that a steeper upper slope reduces the amount of stones required. The difference is small for the steepest slopes of n = 4/3 and 1.5. The lower slope has less influence on the amount of stones required. Based on Figure 8, the lower and upper slopes were chosen for m = n = 1.5. The berm length becomes b = 19 m (Fig. 7). This choice of berm breakwater dimensions and the profile after design conditions is shown in Figure 9.

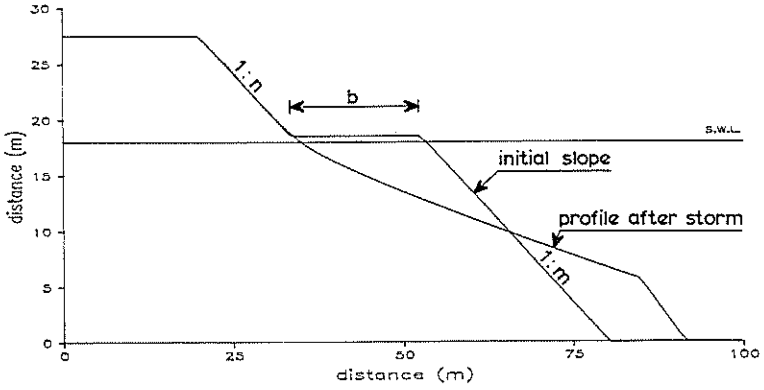

Figure 9 Berm breakwater with m = 1.5, n = 1.5, b = 19 m and profile after 1/50 years storm

Influence of water depth

With the lower and upper slopes fixed at 1:1.5 the berm length becomes 19 m for a water depth of 18 m. The berm length can be reduced in shallower water using the same design conditions. Figure 10 shows this reduction of b for shallower water.

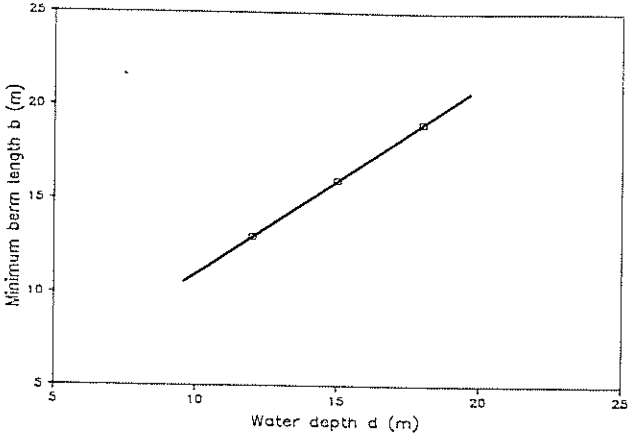

Figure 10 Influence of water depth on minimum berm length

Influence of stone class

Upto now the wide gradation of 0.5-9 t with D_{n50} = 1.01 m was used. Heavier stone will show less displacement of material. Therefore the profiles under design conditions were computed for the stone classes 1-9 t and 3-9 t according to output curves of a view quarries. Figure 11 shows all three profiles. As the differences in D_{n50} are small, the differences in profile are small too. It can be concluded that the wide (and cheaper) class of 0.5-9 t is satisfactory.

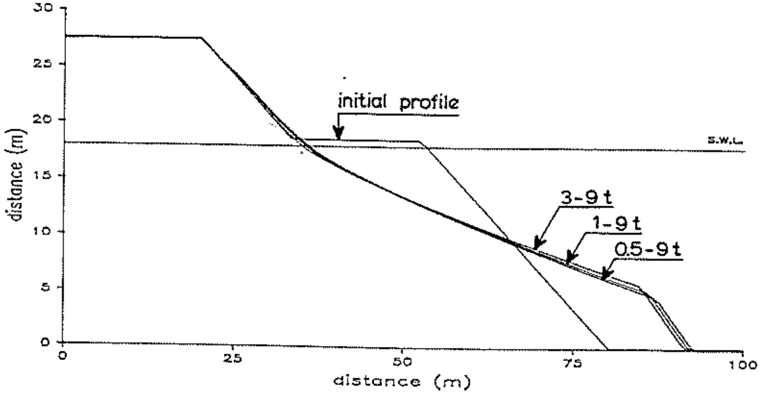

Figure 11 Influence of stone class

Influence of wave climate

The berm breakwater was designed for H_s = 7.6 m, T_z = 10.0 s and a storm duration of 6 hours, being the 1/50 years condition. The structure, however, will show profile changes for much lower wave heights. Therefore, the profile was calculated for a wave height of H_s = 4.7 m, being the 1/1 year wave height. It is furthermore interesting to know the influence of a higher wave height than the design wave height. Another profile was calculated for H_s = 9.2 m, being the 1/400 years wave height. The profiles are shown in Figure 12. The highest wave height shows some erosion of the upper slope, but under these circumstances some erosion can be allowed. The armour layer should be thick enough, however.

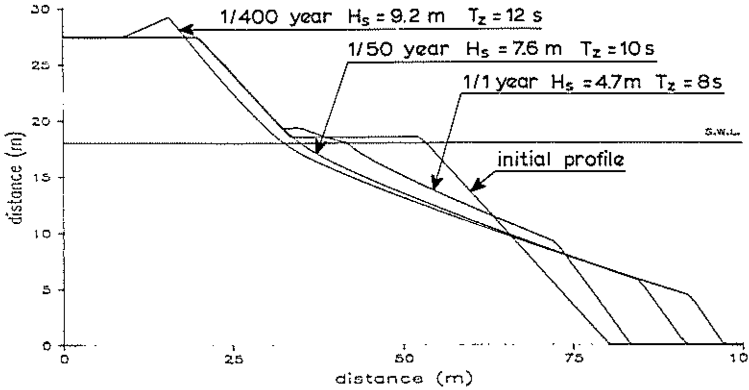

Figure 12 Influence of wave conditions

The wave period has influence on the profile and is often an uncertain factor in the design. The profiles for a lower wave period (T_z = 8 s) and a higher wave period (T_z = 12 s) were calculated and shown in Figure 13, together with the period of 10 s. The longer period gives again some erosion of the upper slope.

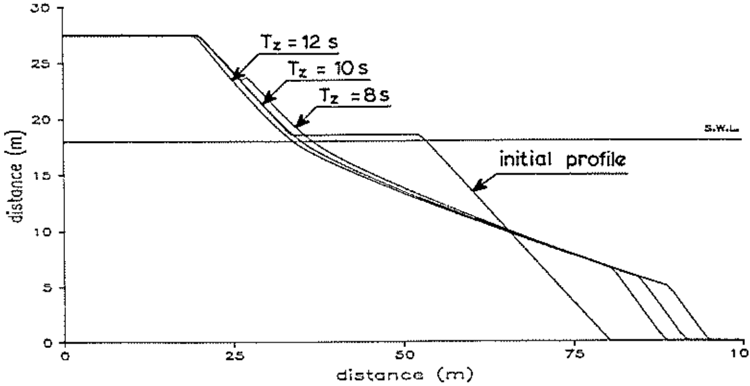

Figure 13 Influence of wave period

Finally the influence of the storm duration can be investigated. Profiles for a storm duration of 6, 12 and 24 hours are shown in Figure 14. The influence is very small. Erosion increases a little and the material is transported downwards.

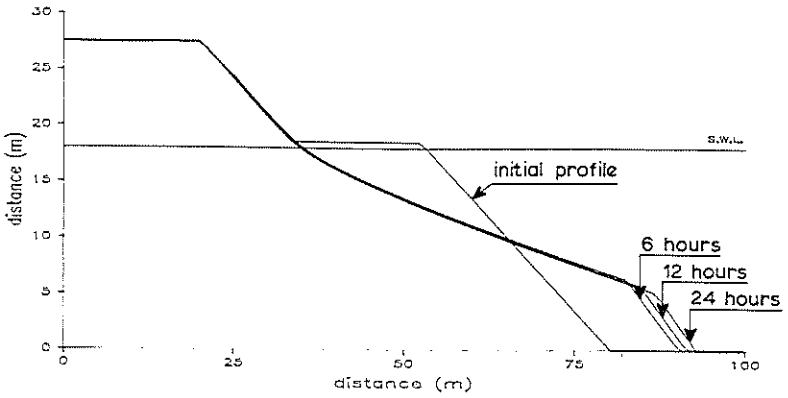

Figure 14 Influence of storm duration

Static stability

The computational model is valid for structures under dynamic stability. This means that if the wave height is too small, or the diameter too large, a profile can not be calculated with this model. The structure must then be considered as statically stable. New stability formulae (Van der Meer (1987)) can be applied in that case. The transition from dynamically to statically stable structures depends on the $H_s/\Delta D_{n50}$ value, but also on the equivalent slope angle. A gentler slope is more stable than a steep slope.

First profile changes to the berm breakwater will occur for relatively low wave heights. More severe storms will change the profile again. But how stable is the berm breakwater after its first profile changes? Consider the profile after the 1/1 year storm with $H_s = 4.7$ m. The profile is shown in Figure 12. The equivalent slope of the profile around the still water level is about 1:3.6. Choosing this equivalent slope, a damage curve can be drawn for static stability (Van der Meer (1987)). This curve is shown in Figure 15. Start of damage occurs for S = 2-3 and about one layer of stones is removed for S = 8-12. From Figure 15 follows that after the 1/1 years storm the structure will act as statically stable upto $H_s = 6$ m. In that case about one layer of armour stones will be displaced. For higher wave heights the profile will change more and will become dynamically stable again.

Other applications

The computational model can be used to describe the behaviour of rock and gravel beaches, including the influence of storm surges and tides. It can also be used to design a two-layer S-shaped breakwater. The length and slope of the gentle part of the S-shaped breakwater can be estimated and also the steeper upper and lower slopes. Another application is the prediction of the behaviour of core and filter layers under construction when a storm hits the incomplete part of a breakwater.

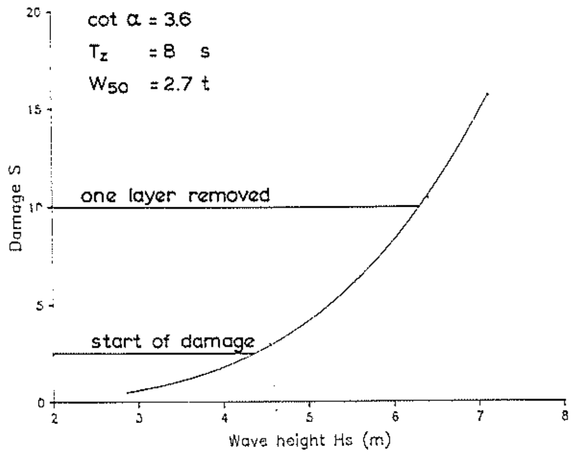

Figure 15 Damage curve for a statically stable homogeneous structure with an equivalent slope 1:3.6

Conclusions

The development of a computational model on dynamic stability has been summarized. This model was used to design a berm breakwater. The optimum dimensions of the breakwater were calculated with respect to the minimum amount of stone required for construction. The 1/50 years design conditions were used for this procedure. Influences of water depth, stone class, and wave climate were investigated. Finally the transition from dynamic to static stability was studied in more detail.

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